Undergraduate Thesis

Strategies underlying bimanual force sharing in humans

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Abstract

Force sharing refers to the way that the brain and body parts work together to apply forces to complete tasks. Bimanual force sharing involves using both arms to complete tasks. Force sharing allows humans to complete many daily tasks and requires a good deal of control. Even though force sharing is intuitive for many people, the concepts behind it are still not well understood. The inability to force share can decrease the quality of life since many daily tasks require force sharing and control. The goal of this research was to contribute to the current knowledge of force sharing by simulating a force sharing task between two arms on one able-bodied person. To simulate the force sharing task, two force plates were used. The subject pressed on each plate with one hand with the goal of reaching a desired force. The forces applied to the plates were added together to try to reach the goal force. In each trial, the goal force was varied as well as the fraction contribution of each plate to the force output. By varying both parameters, a range of force sharing tasks was simulated with different levels of task symmetry. We hypothesized that people will produce systematically higher forces for the side that contributes more to the weighted force output. The data suggested that the subjects generally applied more force to the force plate with the greater contribution, but not always. To see if exertion level affected the results, trials with differing goal forces were compared. The data showed that with higher exertion levels, the standard deviation of the force output increased. However, the conclusions from the data cannot be applied to the general population due to the small sample size. Future work could expand the study to more subjects and considering various protocol variants could increase our understanding of force sharing and control.

Acknowledgements

I would like to thank Dr. Manoj Srinivasan and Sriram Muralidhar for their help and guidance during this project. I also thank Dr. Derek Hansford for serving on my defense committee.

I would also like to thank the subjects who volunteered to participate in the study, given the current situation with COVID-19.

Lastly, I would like to thank the College of Engineering for supporting this project and providing their guidance.

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Chapter 1: Introduction

Force sharing is a skill that many humans are able to perform innately to complete daily tasks. Some examples of daily tasks that require force sharing and bimanual coordination—that is, force sharing and coordination between the hands—can be seen in Figure 1.

Fig. 1. Activities of daily living requiring bimanual coordination.

Figure 1: Examples of daily tasks that require force sharing and control (Lum et al., 1993).

Bimanual force coordination allows for the completion of a wider range of tasks compared to unimanual force application (Talvas et al., 2014). In addition, bimanual tasks can be categorized as either common goal or dual goal. In common goal tasks, both hands work together to meet the same goal. Dual goal tasks differ in that each hand has a different independent goal (Liao et al., 2018). Dual goal tasks can be difficult sometimes, such as drawing a square with one hand while drawing a circle with the other. This difficulty is affected by both the cognitive and physical domains, which makes studying dual goal tasks complex (McAmis and Reed, 2012).

When force sharing, humans distribute forces across two or more body parts with coordination and control. One example of a force sharing task is carrying a bowl of water. As the hands carry the bowl, they must support the load, so they do not drop the bowl and also keep the bowl level so no water spills. Force sharing can occur between different parts of a single human or between two or more humans, which makes the skill important not only for individual tasks but also working with others to complete tasks. An example of force sharing between more than one person is carrying a couch with someone. As two people carry a couch, their arms account for the fact that the couch may be an asymmetrical load while also accounting for the fact that someone else is carrying the other end. Coordination is also possible between the arms and the legs simultaneously, allowing for even more possible force sharing tasks (Fujiyama et al., 2010).

1.1: Literature Review

When studying bimanual force sharing in chronic stroke patients, Patel and Lodha found that total force output in chronic stroke participants was 53.10% less accurate and 56% more variable than the control group (Patel and Lodha, 2019). Their results show that force sharing is significantly affected by stroke, making force sharing research clinically relevant. Since stroke commonly causes motor asymmetry, rehabilitation of force sharing is of interest in the medical community. Another study on motor control and age found that older adults had a lower ability to control forces in their hands (Jin et al., 2019). Decreased motor control can limit one's ability to perform daily tasks and reduce the quality of life. The results of this study show another potential need for motor control rehabilitation strategies, specifically targeting force control. One rehabilitation strategy that is being developed involves using transcranial direct current stimulation (tDCS) to improve bimanual force control (Jin et al., 2019). The authors found that tDCS of the left primary motor cortex resulted in improved accuracy of force tasks. Their results show the potential of neuroscience research to aid in the study of force sharing and control. Neuroscience-based rehabilitation methods show promise in improving motor learning and control.

Another related field of interest is the development of force sharing robotic devices. These devices could assist humans in performing a range of tasks. For example, robotic devices could be used for physical therapy or haptic interfaces (Lum et al., 1993, Endo et al., 2011). For rehabilitation, robotic devices could be used to help patients regain force sharing and control abilities. Understanding human bimanual force sharing can inform the development of such devices so that their behavior is akin to natural human abilities.

1.2: Research Significance

The inability or decreased ability to force share can be seen in patients with asymmetries. Such asymmetries can be caused by diseases such as stroke or Parkinson's disease. Decreased force control can also be seen in older adults, adding to the clinical relevance of force sharing research. Since force sharing and control are widely used for daily tasks, the loss of these skills can decrease the quality of life. Understanding force sharing in healthy humans can help inform rehabilitation strategies for patients with decreased ability to force share and control.

Force sharing research can also be applied to the development of robotic devices. Robotic devices can potentially be used in a rehabilitation context to help patients regain force sharing control. In addition, force sharing concepts could be used to develop robotic devices that help humans complete tasks. Such devices could expand the boundaries of human ability by enabling the completion of tasks that would not be possible for a human to complete naturally. In a broader sense, force sharing concepts could be used to help robots complete a wider range of tasks.

While the concepts of force sharing can be applied to many fields, the underlying motor control strategies and mechanisms are still not well understood. Further research is needed to develop these applications and help them reach their potential.

1.3: Overview of Thesis

Bimanual force sharing in particular involves the use of both arms and/or hands to do activities. Bimanual force sharing—using both hands to produce a net external force—is an inherent skill for humans. Since the concepts behind bimanual force sharing are still not well understood, the goal of our project was to collect and analyze force sharing data in an effort to contribute to this understanding. We did so by simulating different force sharing tasks and observing subjects' response to them. Our force sharing tasks involved applying downward vertical force to two force plates, one with each hand. Between trials, each force plate contributes differently to the weighted force output, which the subject tries to match to a goal force. Our **hypothesis** is that people will produce systematically higher forces for the side that contributes more to the weighted force output. Our prediction is consistent with energy optimality (Srinivasan, 2011), combined with the similar properties for the two hands.

The remaining chapters elaborate on the project, detailing methods, results, and the conclusion. The methods chapter will describe the experimental setup and design as well as data collection. The results chapter will present our human subject data and describe how humans systematically changed their force exertion with their two hands depending on the task asymmetry. Lastly, the conclusion chapter will cover contributions, limitations, future work, and a summary.

Chapter 2: Methods

A substantial fraction of the project focused on developing the experimental design to reach the research goals mentioned earlier. In this chapter, we will describe the methodology used for data collection, along with the limitations and adjustments that were made throughout the experimental design process.

2.1: Experimental Design

Inclusion and exclusion criteria: Since the research will study force sharing between the arms, the subjects will need to be able to apply varying amounts of force with both arms. They will also need to have fine control of the force they can apply with their arms. The experiment is slightly strenuous, so healthy adults of ages 18-60 will be able to participate. We will exclude subjects who are pregnant or have preexisting heart or lung conditions. Based on prior biomechanical studies, we expect that a sample size of about 10 will be able to provide statistically significant results regarding force sharing.

Materials:

- Bertec force plates
- Zomei tripods
- Platforms on tripods to apply forces on
- Vicon Nexus DAQ system
- Computer with MATLAB
- Two monitors (one for the experimenter, one for the human subject)

Experimental design: The goal of the experimental design was to simulate a bimanual force sharing task, perhaps in the simplest possible manner. The original vision for the experimental setup planned to use two Bertec force plates and two tripods with mounted horizontal platforms, and it can be seen in Figure 2. The vision for the experimental setup was realized using the setup shown in Figure 3.

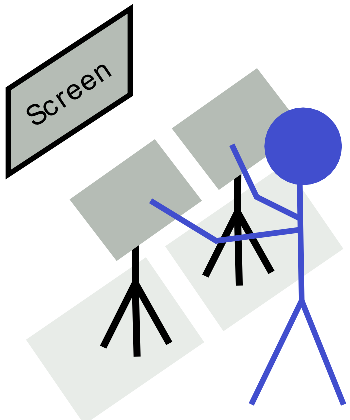

Figure 2: Original vision for the experimental setup. The subject presses down on the platforms mounted on top of the tripods, which each sit on top of a force plate. A screen is placed in front of the subject to give them prompts.

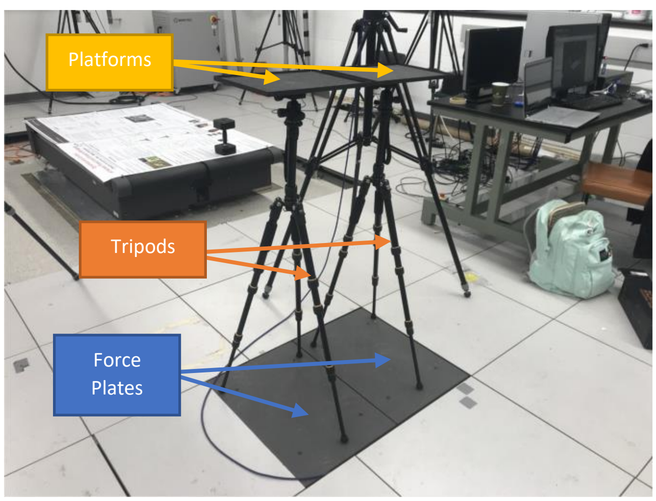

Figure 3: The experimental setup used to collect force data from each arm.

The tripod platforms provided a surface for the subject to apply forces to with each hand. Since each tripod stood on a force plate, any forces applied to the platforms were transferred to the force plates. Two force plates were used so the subject could apply forces with each arm simultaneously.

Say F_L is the vertical force exerted by the left hand and F_R is the vertical force exerted by the right hand. To simulate a force sharing task, we defined an output force F_{output} that depends on both forces F_L and F_R: specifically, F_{output} is a linear combination of the two forces as shown below in Equation 1, scaled by λ and (1- λ) respectively.

$$F_{output} = \lambda F_L + (1 - \lambda) F_R \tag{1}$$
$$F_L = left\ hand\ force$$
$$F_R = right\ hand\ force$$
$$\lambda = weighting\ parameter$$
$$F_{output} = weighted\ force\ output$$

The task that the subject aimed to complete involved trying to match F_{output} to a goal force, F_{goal}. In this equation, the weighting or scaling parameter λ can be varied to change how each force plate contributes to the weighted force output. For example, for a λ value of 0, the left force plate does not contribute to the force output, leaving the right hand force as the sole contributor to F_{output}. When λ has a value of 0.3, both force plates contribute to F_{output}, but the left force plate contributes less to the force output than the right plate. Thus, the λ value decides how "symmetric" the scenario is and any λ different from 0.5 results in an implicitly asymmetric scenario. For each trial, we chose λ to have a value from the following set: {0.1, 0.3, 0.5, 0.7, 0.9}. The λ value was be randomly selected for each trial to simulate a range of force sharing tasks. Having a goal for the linear combination of the forces is physically equivalent to having the left and the right forces together apply a moment, where λ and (1-λ) are analogous to moment arms.

Since we expected that exertion level would affect the results, we incorporated different levels of exertion into the experimental design. To do so, we created different goal forces using Equation 2, which can be seen below.

$$F_{goal} = \alpha F_{max} \tag{2}$$

$F_{goal} = goal\ force$

$\alpha = exertion\ parameter$

$F_{max} = maximum\ force\ subject\ can\ apply$

To calculate the goal force, the maximum force the subject can apply (F_{max}) was multiplied by α. To create two different exertion levels, α had a value of either 0.4 or 0.7. At the beginning of the experiment, F_{max} was collected so that it is customized to each subject's strength. By doing so, we were able to somewhat normalize the level of exertion across all subjects. In both the experiments and in the analysis, we considered only the vertical forces and did not examine the horizontal forces applied.

A MATLAB program was used to display the goal force and weighted output force to the subject. For each trial, the display of these forces looked the same, so the subject was unable to determine the goal force or the λ values for the force plates. Figure 4 shows the display that the

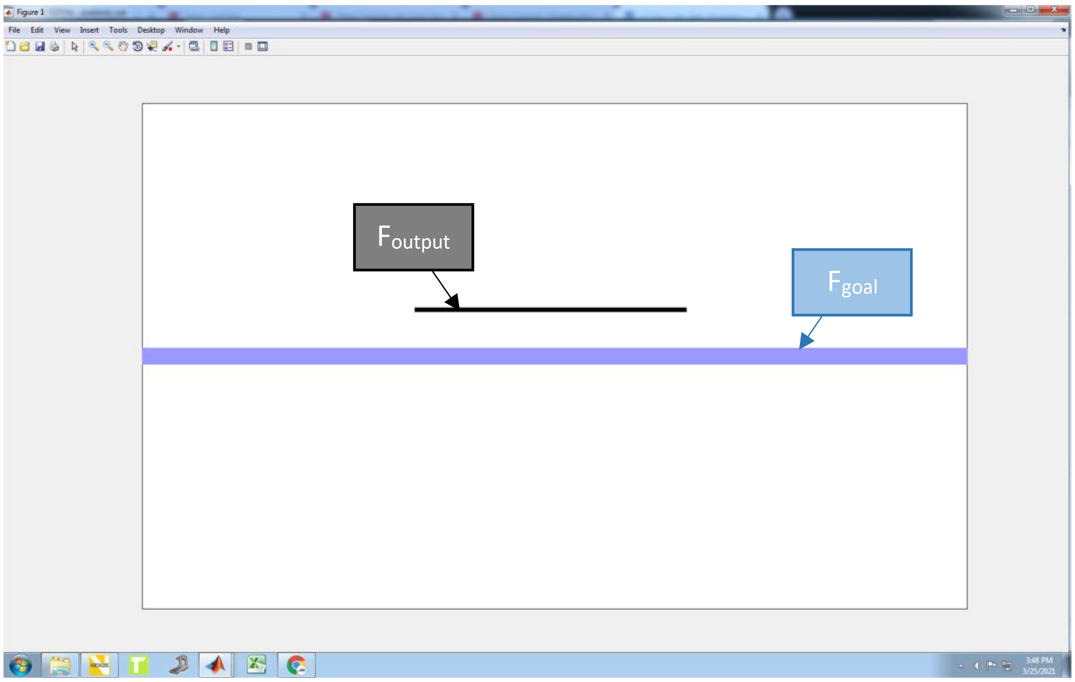

Figure 4: Screenshot of display that the subject sees during a trial. The light blue horizontal line represents the goal force (F_{goal}), which remains constant and stationary throughout the trial. The short black horizontal line represents the subject's weighted force output (F_{output}), which varies throughout the trial.

subject sees during each trial.

With 5 different λ values and 2 different α values, a total of 10 trials were collected for each subject. Each trial was 4 minutes long to give the forces time to stabilize. Subjects were given a 10 second break between each trial.

When the data acquisition system was first powered up for data collection, the force plates were zeroed through the Vicon program and by holding down the zeroing buttons on the amplifiers for at least 6 seconds. This zeroing process was done with the tripods sitting on top of the force plates so that the weight of the tripods did not contribute to the subject's calculated force output.

2.2: Data Collection

Procedure before data collection: Prior to data collection, the subject's dominant arm was noted as well as their age, sex, height, hip height, and weight. Measurement of the hip height involved measuring the distance between the top of the subject's iliac crest to the floor. The hip height was used to adjust the heights of the tripods, customizing it to the subject. Figure 5 shows the component of the tripod that was aligned with the subject's hip height during tripod adjustment.

Figure 5: An image of the top of the tripod (with platform mounted) with a red rectangle indicating the component of the tripod that was aligned with the subject's hip during tripod adjustment.

Once the tripods were adjusted, they were placed on the force plates. The horizontal platforms were inspected to see if they were screwed on tightly to the tripods and were retightened as necessary. The horizontal platforms were then sanitized, and the subject was asked to stand in front of the tripods. While the subject was standing there, the instructions were read to them and they were asked if they had any questions before starting the trials. The instructions given to the subject can be seen below:

> "For each trial, you will have to press down on the platforms with your hands to reach a goal force. You will press on the left platform with your left hand and the right platform

with your right hand. Try to do whatever feels comfortable. You don't have to press equally hard with both hands. Sometimes you may feel it's better to press more with one hand than the other, and sometimes it may be better to press with both hands equally. Each trial is different, so do whatever feels comfortable on each trial.

There are going to be 10 trials that are 4 minutes each, and you will be given a 10 second break in between trials. During each trial, the goal force will be represented on the screen by a light blue horizontal line. Your force output will be shown as a horizontal black line, which will move as you apply forces to the platforms. Make sure that you are not standing on the force plates and that you are not leaning over the horizontal platforms. Your arms should be gently outstretched so that your hands can press down vertically on the platforms. Before the trials begin, there will be two short "pre-trials". In the first pre-trial, do not apply any forces to the platforms. For the second pre-trial, apply as much force as you can to each platform at the same time."

The same script was used for all subjects. Thus, the subjects were told something about the task asymmetry, but did not know more about how the output force was computed or the λ value. The subject viewed the prompts for the trials on a computer monitor sitting on the desk to the right of the force plates. The monitor was positioned so that the subjects could see it easily.

Data collection code: The code first started with two pre-trials: one for calculating the zero offset and one for calculating the subject's maximum force.

In order to combat some noise of the force plates, the MATLAB program first collected force data for 10 seconds while no force was applied to the plates (only the tripods stood on the plates). The average force during this time period was calculated and stored in MATLAB as a zero offset. During each trial, this offset was subtracted from the calculation of F_{output} to remove small systematic offsets, essentially zeroing the force plates with the tripods on them. At the end of this pre-trial, a pause was included so that the experimenter could continue the program when the subject was ready.

Before the first trial, the MATLAB program collected a baseline that was used as the maximum force value (F_{max}). This collection involved the subject pressing both platforms simultaneously as hard as they could for 10 seconds. The MATLAB program then took the average force value of each arm over the last 5 seconds of the pre-trial and calculated the minimum of the two values. This minimum value was set as the F_{max} for the rest of the trials. As with the zero offset pre-trial, the maximum force pre-trial ended with a pause that required a keystroke to continue to the next section of the program.

Once the zero offset and maximum force pre-trials were complete, the trial section of the program began. Each trial lasted 4 minutes, with the display from Figure 4 shown to the subject for the whole trial. After each trial, a pause was included in the program so the experimenter could control when the program progressed to the next trial. After all of the trials were complete, the program wrote pertinent data to .mat files, including data from both pre-trials and all ten trials. The raw force data was negative in the Z direction, and the code negated it to facilitate later analysis. So, in the exported force data, a positive Z force corresponds to a downward force.

Procedure during data collection: When the data collection program begins, we first perform the two pre-trials described in the previous section, then the ten trials. Between each pre-trial and trial, the subjects were given a 10 second break. When the program paused between each pre-trial/trial, the spacebar was pressed to advance the program to the next trial. When the subject completed five trials, they were informed that they were halfway through the trials. After data collection was complete, we checked to make sure the data files saved correctly onto the computer. Once the data was confirmed, the subject was told that they would receive compensation and that they were free to leave.

Due to COVID-19 restrictions, we were able to collect data from only three subjects. One of the subjects was left-handed while the other two were right-handed.

2.3: Anthropometric Information

A summary of the anthropometric data for all subjects can be seen in Table 1.

Table 1: Summary of anthropometric data.

Subject #	Age	Sex	Weight (lb)	Height (ft, in)	Hip Height (in)	Handedness
1	19	Male	163	5’11”	42	Right
2	22	Male	160	5’10”	43	Left
3	22	Female	175	5’2.5”	39	Right

2.4: COVID-19 Precautions

Due to the pandemic, additional precautions were taken in order to maximize the safety of the subjects and the experimenter. The tripod platforms, which were the only surfaces the subjects interacted with, were sanitized before and after data collection. Social distancing was practiced between the subject and the experimenter, with the experimenter sitting at a desk at least six feet away from the tripods. Both the subjects and the experimenter were required to wear masks at all times.

Chapter 3: Results

The collected data were analyzed in MATLAB, to produce both subject-specific visualizations of the data as well as summary descriptions pooled across all subjects.

3.1: Maximum force trials

Figure 6 shows a sample plot of the forces during the maximum force (F_{max}) pre-trial over time. Even though the F_{max} pre-trial lasted only 10 seconds, the subject was unable to maintain their maximum force output during the whole pre-trial. As a result, the calculated F_{max} was likely lower than the actual subject's maximum force output since F_{max} was calculated by averaging the pre-trial force data. Subject 3's Fmax pre-trial shows a similar trend, whereas subject 1's force generally increased throughout the F_{max} pre-trial. For reference, the F_{max} plots for subjects 1 and 3 can be seen in

Figure 7: 7. In any case, the calculated F_{max} was likely lower than the actual maximum forces

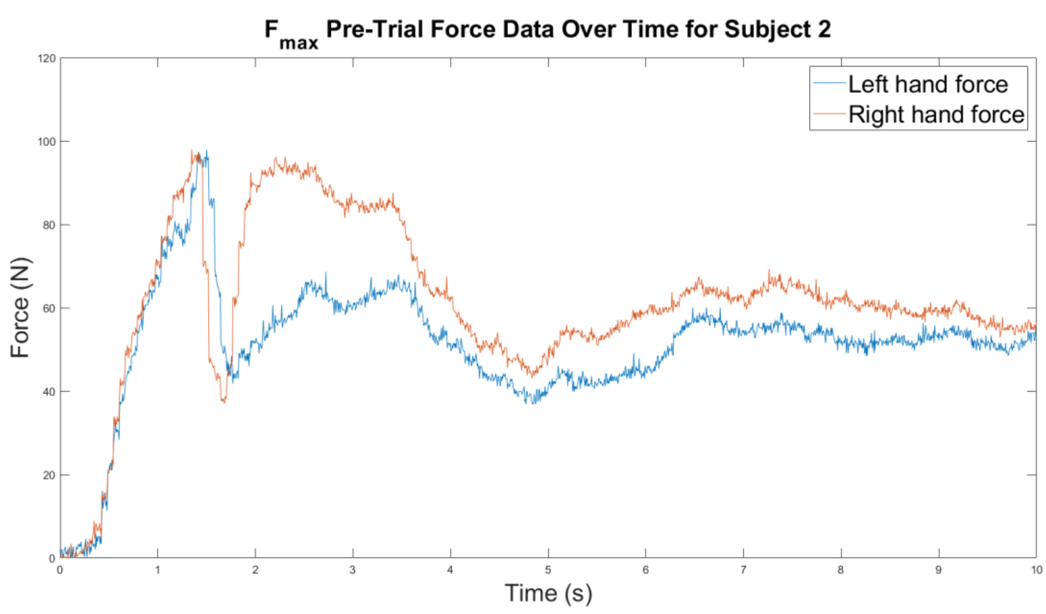

Figure 6: Plot of the left hand (blue) and right hand (orange) Z forces over time during subject 2's F_{max} pre-trial.

that each subject was capable of.

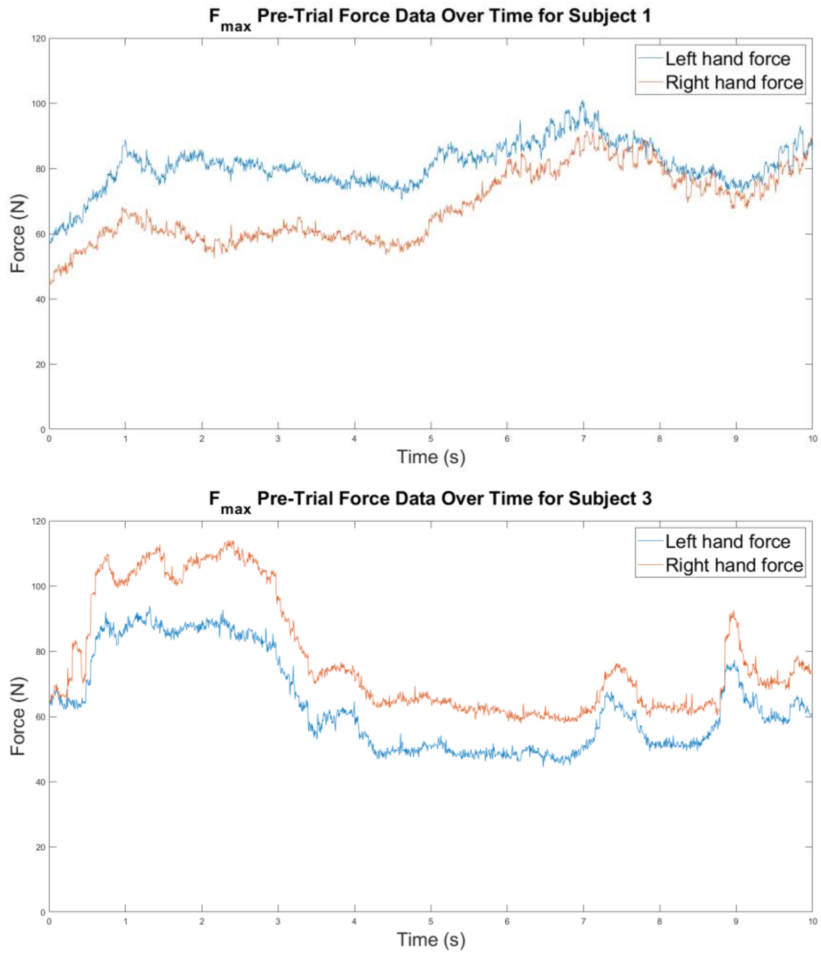

Figure 7: Plots of the left hand (blue) and right hand (orange) Z forces over time during the F_{max} pre-trial for subject 1 (top plot) and subject 3 (bottom plot).

3.2: Illustrating what an individual trial looks like

Next, we show sample plots of individual subject data to illustrate what a typical trial looked like. Figure 8 shows the left hand and right hand Z forces over time for subject 2's fifth trial with $\alpha = 0.4$ (so goal force is 40% of maximum hand force, defined in the last chapter). and $\lambda = 0.5$ (so each hand contributes equally to the output force).

Throughout the trial, the left hand and right hand Z forces were fairly equal, with the left hand Z force being slightly higher than the right hand Z force on average. Both forces fluctuated about the mean substantially with both fast time-scale fluctuations (partly due to sensor measurement noise) and slower time-scale fluctuations (due to real force exertion changes). Since subject 2's left arm is dominant (left-handed subject), we might superficially expect that the left hand force would be larger, on average, than the right hand force, which is shown in this trial, although this is not a trend that we systematically tested in this study. Nevertheless, it could be useful to look

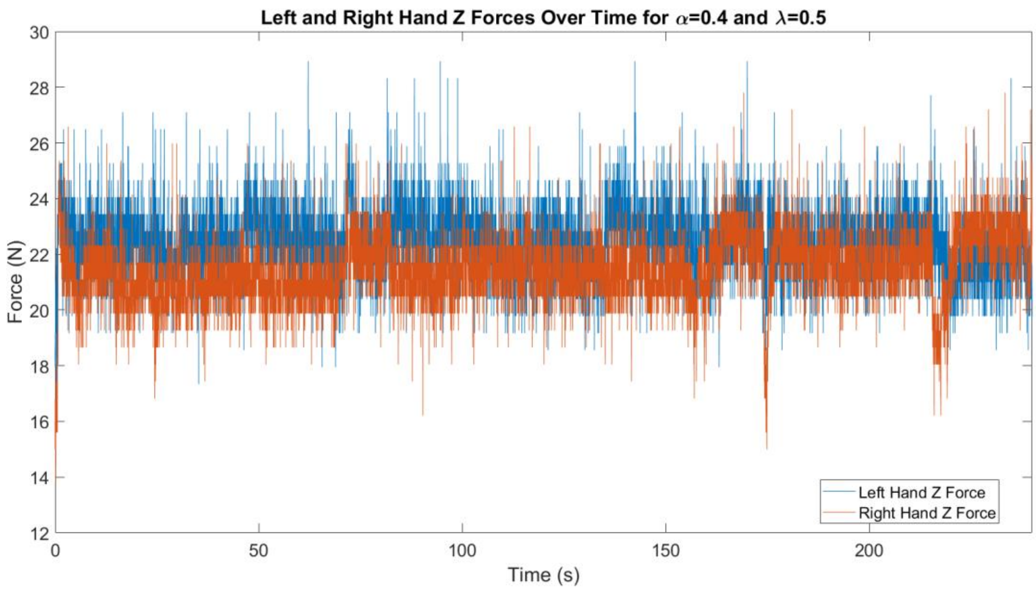

Figure 8: Sample data of the left hand (blue) and right hand (orange) Z forces over time. This data was taken from subject 2's fifth trial. The corresponding α and λ values for the trial are displayed in the title of the plot.

at the same plot corresponding to another subject.

Figure 7 9 shows the left and right hand Z forces over time for subject 3's fifth trial, with the same α and λ values.

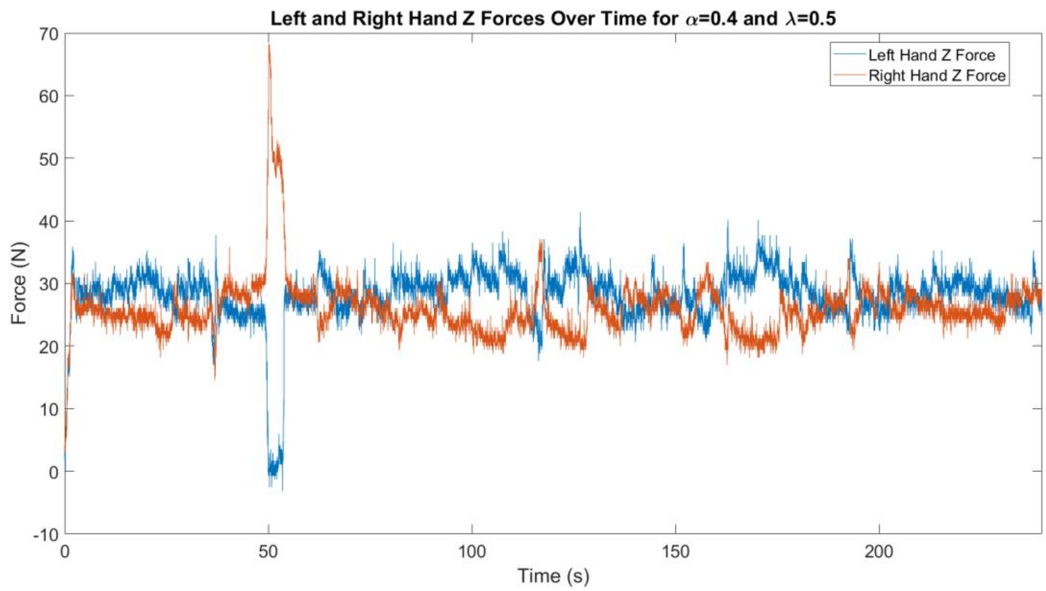

Figure 9: Sample data of the left hand (blue) and right hand (orange) Z forces over time. This data was taken from subject 3's fifth trial. The corresponding α and λ values for the trial are displayed in the title of the plot.

In this plot, the left and right hand Z forces are also similar to each other for most of the trial. For both trials, λ had a value of 0.5, so we expected similar forces from both hands. The data from both subject 2 and subject 3 imply that they matched the λ value fairly well. When looking at fluctuations, subject 3's data had an extreme fluctuations at around 50 seconds. The right hand force deviated upwards while the left hand force deviated downwards. The sudden drops of the left hand force could correspond to the subject momentarily lifting their left hand to adjust its position. Another possibility is that if the left hand was weaker, the subject may have stopped applying force momentarily to give their left arm a break. Since the right hand force deviated upwards, it seems that the subject could have consciously tried to apply more force with their right hand. The short time span of the fluctuation makes it seem more likely that the subject adjusted their right hand's position by pressing slightly on the platform.

Next, we plotted the output force (linear combination of the individual hand forces) over time, along with the goal force, for subject 2's fifth trial. In this plot, which can be seen in Figure **10:** 10, subject 2 keeps their force relatively constant at about 27 N throughout the trial, with a goal force of about 20 N.

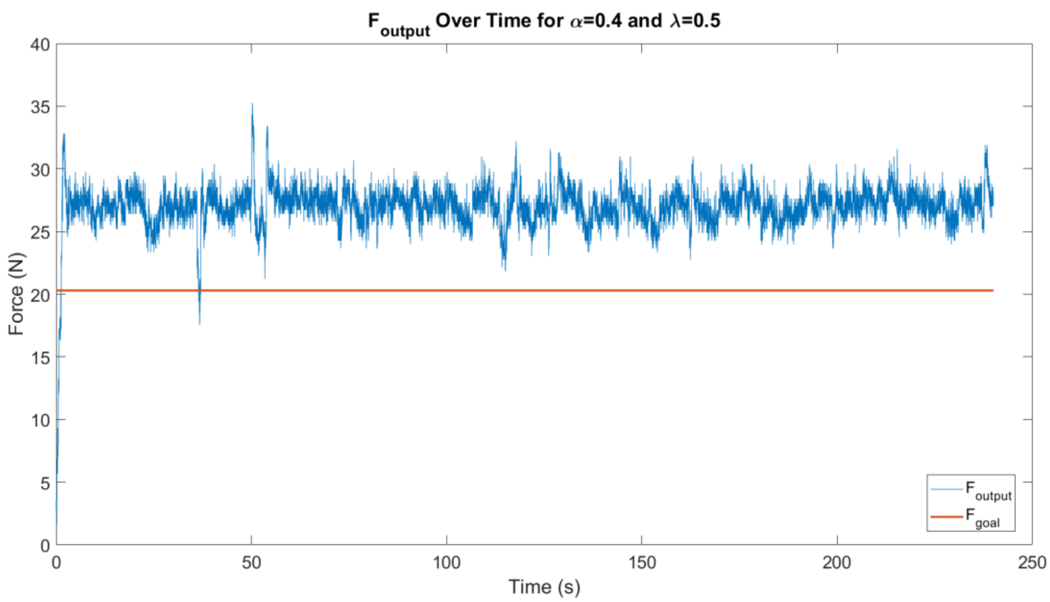

Figure 10: Sample data of the output force over time (blue) along with the goal force (orange). This data was taken from subject 2's fifth trial. The corresponding α and λ values for the trial are displayed in the title of the plot.

The steadiness of the force output implies good overall control of the applied forces. Interestingly, subject 2 demonstrated that they were able to maintain a relatively constant force output, yet maintained that force at around 27 N, about 7 N greater than the goal force. Subject 2's other trials follow a similar trend, with seven out of ten trials having a relatively constant force output above the goal force.

3.3: How well did subjects track the goal force overall?

Figure 11 shows the mean of the ratio between F_{output} and F_{max} versus α using all subjects' data.

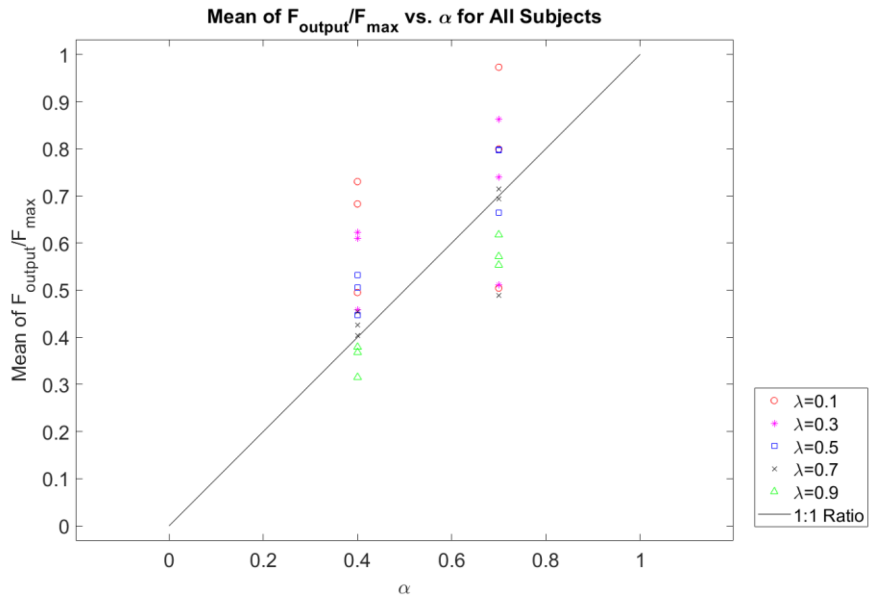

Figure 11: A plot of the mean ratio between F_{output} and F_{max} versus α for all subjects. The different colors and markers of the scatter plot points indicate the different λ values, which are specified in the legend. A line representing a 1:1 ratio between the mean ratio of F_{output} to F_{max} and α is overlaid on the plot.

When the mean of F_{output}/F_{max} is equal to α, the subject is meeting F_{goal} perfectly on average. So, meeting the goal force corresponds to a 1:1 ratio between F_{output}/F_{max} and α, which is shown by a black line on Figure 11 of unit slope. Figure 11 suggests that for the lower goal force (α=0.4), the subjects generally output more than the goal force on average.

It seems that for both extreme λ values (0.1 and 0.9), the subjects had lower output forces and higher output forces on average, respectively, for all subjects thus far. This trend implies that the subjects applied higher output force when the right force plate dominated and lower output force when the left plate dominated. We might superficially expect this trend to perhaps differ between right- and left-handed subjects, so it is interesting that this trend was quite strong even though one subject is left-handed.

3.4: Within trial variability in subjects

Subjects had substantial variability in their forces within each trial, as shown in Figure 12, which displays the standard deviation of the force ratio versus α.

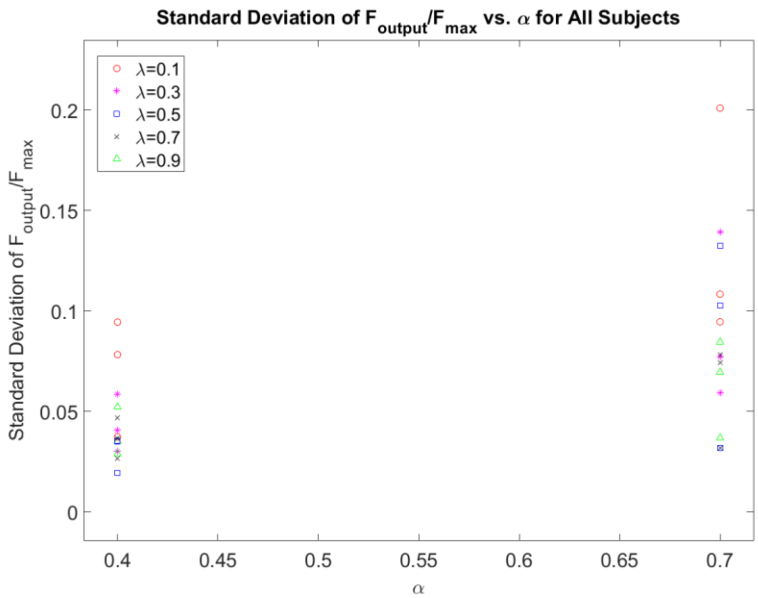

Figure 12: A plot of the standard deviation of the ratio between F_{output} and F_{max} versus α for all subjects. The different colors and markers of the scatter plot points indicate the different λ values, which are specified in the legend.

As α increases, we expect to see a higher standard deviation corresponding to less control and indeed, it seems that, on average, the standard deviation is higher for the higher goal force trials. The average of the F_{output}/F_{max} standard deviation when $\alpha = 0.4$ is 0.044 while the average force ratio standard deviation when $\alpha = 0.7$ is 0.088. However, since there are only 15 data points per α value, the average calculations may be significantly affected by outliers.

The trials with a λ value of 0.1 seem to have relatively high standard deviations compared to the rest of the trials. This observation reflects the similar trend that was found in the plot of the means in Figure **11:** 11. Since the trials with $\lambda = 0.1$ displayed higher mean forces generally, they corresponded to a higher level of exertion. We expect that with a higher level of exertion, the standard deviation would increase as control decreases, which is illustrated in the standard deviation plot. The phenomenon of higher force variance when the mean force is higher is called signal dependent noise (Harris and Wolpert, 1998), and it may explain the higher standard deviation as the goal force increases.

3.5: How symmetric were the subjects overall?

We now present summary plots using data from all three subjects. First, we plotted the ratio between the mean right hand force (F_R) and the mean total force (F_R+F_L) as a function of lambda over the whole trial. The described force ratio represents the average fraction contribution of the right hand force to the total applied force (not F_{output}), seen in Figure 13, along with box plots for each group of data points corresponding to one λ value.

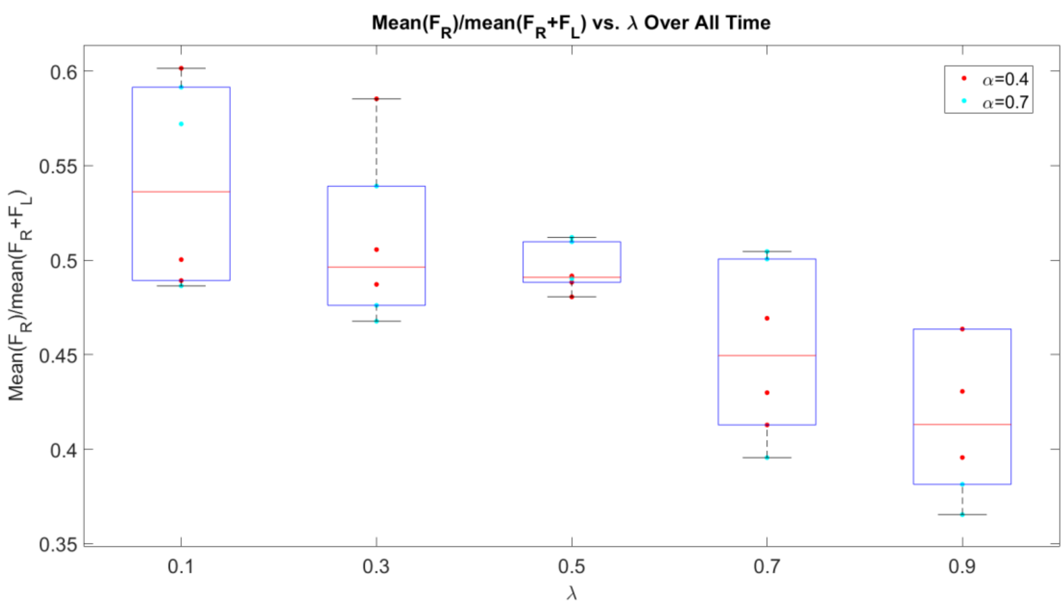

Figure 13: A plot of the ratio between the mean right hand force and the mean of the summed forces versus lambda. The means were taken over the entire trial time, and the plot includes data from all subjects. The two different colors of the scatter plot points indicate the two different α values, which are specified in the legend. Box plots were added to the data set corresponding to each λ value to help evaluate trends.

Based on the box plots, the median force ratio described above decreases as λ increases. As λ increases, the left force plate contributes more to the force output, so we hypothesized that the subjects would apply more force with their left hand. The data suggests that this trend occurs since a decreased force ratio corresponds to a decreased contribution from the right hand.

3.6: Do people become more or less asymmetric over time?

We made two more similar plots to Figure 13, with one taking the mean across the first two minutes of the trial and the other taking the mean across the last two minutes. The plots corresponding to the first two minutes and last two minutes can be seen in Figures 14 and 15, respectively. Both were qualitatively similar, with the median force ratio decreasing as λ increases. While it is not possible to perform statistical tests with so few subjects, it appears that there were no visually obvious systematic differences between the first two minutes and the last two minutes in terms of the force ratios.

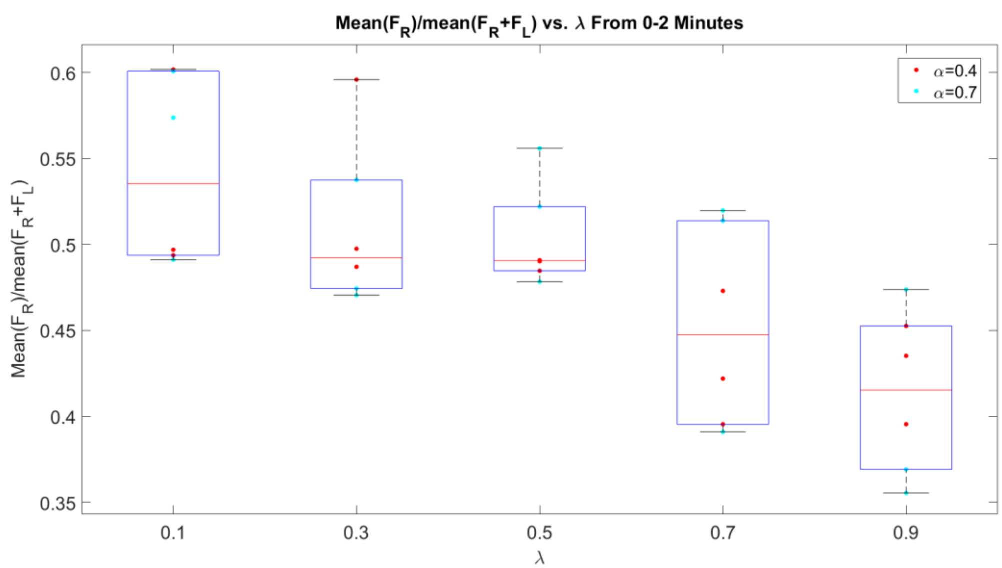

Figure 14: A plot of the ratio between the mean right hand force and the mean of the summed forces versus lambda. The means were taken over the first two minutes of each trial, and the plot includes data from all subjects. The two different colors of the scatter plot points indicate the two different α values, which are specified in the legend. Box plots were added to the data set corresponding to each λ value to help evaluate trends.

We expected that the subject would "learn" over time, perhaps varying their force output in order to find the easiest way to complete the trial (by applying more force on the plate with the higher contribution), becoming more asymmetric for more extreme λ values, but these three plots suggest otherwise.

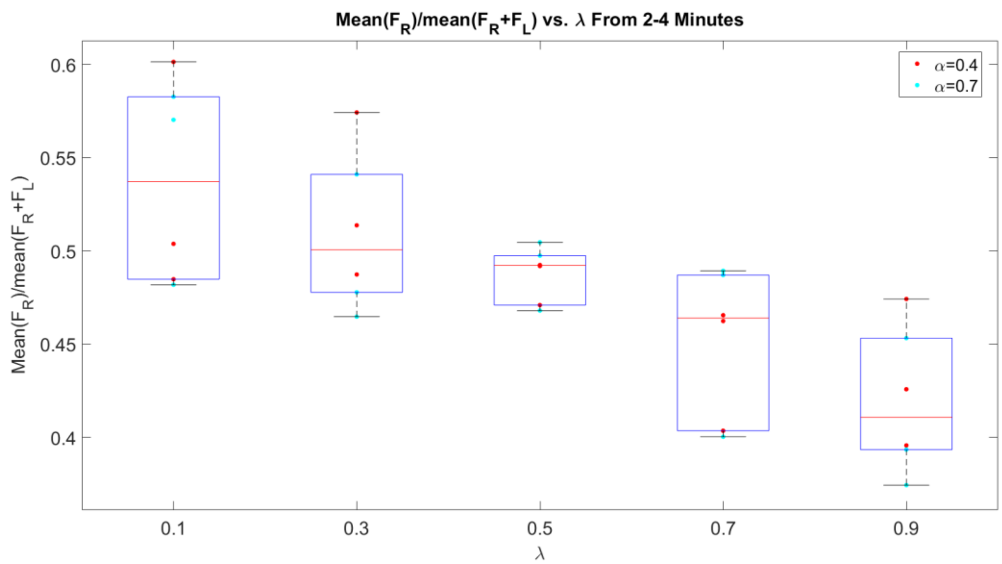

Figure 15: A plot of the ratio between the mean right hand force and the mean of the summed forces versus lambda. The means were taken over the first two minutes of each trial, and the plot includes data from all subjects. The two different colors of the scatter plot points indicate the two different α values, which are specified in the legend. Box plots were added to the data set corresponding to each λ value to help evaluate trends.

3.7: Further remarks on within trial force fluctuations

Next, we plotted the ratio between the right hand force and the total applied force over time in an effort to observe any trends in the force ratio over time (Figure 16). This force ratio represents the fraction contribution of the right hand to the total applied force. Four plots were made for four different trials with combinations of the following parameter values: α = {0.4, 0.7} and λ = {0.1, 0.9}. In each plot, the fraction contribution of the right hand over time was plotted for all three subjects.

For trials with λ = 0.1, the right force plate predominantly contributes to the force output. So, we

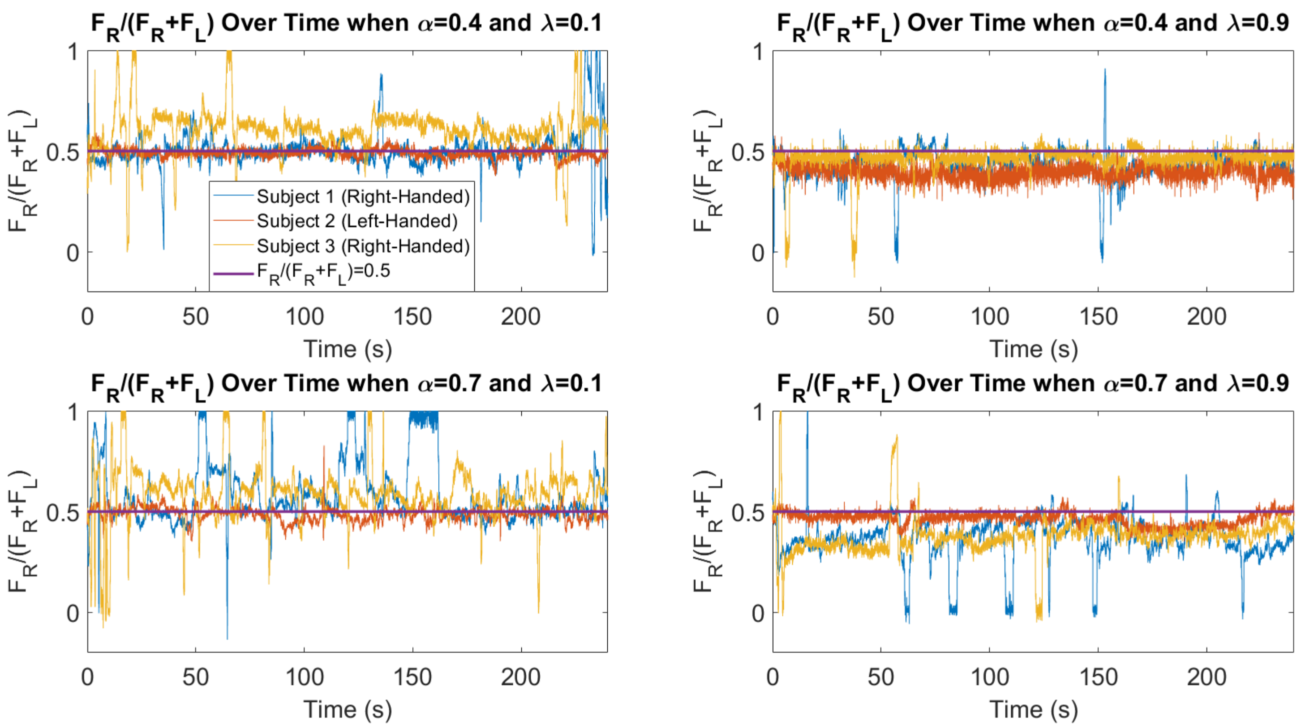

Figure 16: Four plots of the ratio between the mean right hand force and the mean of the summed forces over time. Each plot corresponds to a different trial with specific α and λ values. To facilitate analysis, a horizontal line representing equal contribution from each hand was also plotted. The legend in the top right plot corresponds to all four plots.

would expect to see a right hand contribution of greater than 50% for all subjects. When looking at the two plots that correspond to λ = 0.1, it seems that the right hand contribution is greater than 50% on average, which aligns with our expectation. For the trials with $\lambda = 0.9$, we would expect to see a right hand contribution of less than 50% for all subjects. In the two plots corresponding with this lambda value, it seems that, on average, the right hand contribution is less than 50%, which is consistent with our expectation.

Out of the three subjects, subject 2 kept their right hand contribution the closest to 50% on average. This is interesting because subject 2 was the only left-handed subject. However, we would need data from more subjects (with a fair number of left-handed subjects) in order to see if this trend correlates to the handedness.

Chapter 4: Discussion, Future Work, and Conclusions

4.1: Contributions

During this project, we designed a simple force sharing task with the goal of studying bimanual force sharing. We performed human subject trials with the designed experimental setup and analyzed the resulting data. The data indicated that the subjects showed some asymmetry in their exerted forces when the task is asymmetric (although not always), even though they were not consciously aware of this asymmetry.

4.2: Limitations

Due to the low sample size, the observed trends may not be able to be applied to the general population. The results were likely affected by each subject's individuality due to the very small sample size. In addition, there was only one left-handed subject, so comparisons between right- and left-handed subjects could not be made with much certainty. We did not perform statistical testing due to the small sample size, but we will once we have sufficiently many subjects. The subjects also displayed significant exertion during the trials, particularly during the trials with the higher goal force. The perceived exertion level also tended to increase as trials went on because the subjects may have become fatigued. These factors could make the effect of exertion increased in the later trials, which is not ideal since we intended to control the exertion only by varying the goal force.

4.3: Future Work

There are many possible elaborations that could be added to the experiment to either improve it or study a different aspect of force sharing. To provide more data, a larger set of α and λ values could be used. Assuming the use combinations of every possible α and λ to create trials, increasing these sets would lead to an increase in trials. The trial time could also be increased, which would give subjects more time to learn and adjust their forces. Perhaps having to apply forces over a longer period of time would incentivize subjects to be closer to energy optimality. Collecting data from more subjects would also allow us to apply the results to the general population, and we plan to continue to run trials on human subjects. Once we have data from at least ten subjects, we plan to analyze the data using statistical testing. In addition, we would try to ensure that a significant number of the subjects are left-handed to allow comparison between right- and left-handed subjects.

Some more significant elaborations are possible as well. For example, we could allow the λ value to change over time during the trial, which would require a more varied response from the subjects. In addition, the equation for F_{output} could be changed such that F_{output} would be a nonlinear function of the right and left hand forces. Since the current experimental setup involves two force plates, it could potentially be applied to the study of force sharing between two people, with each person applying force to one plate.

To address the exertion limitation, several possible changes could be made to make the trials less tiring. For example, the trial time could be decreased, the maximum goal force could be decreased, or the break time between trials could be increased. The first two possibilities would limit the scope of the data, so increasing the break time to allow the subjects more time to recover would likely be the best option for decreasing exertion disparity between trials.

Finally, the observed human behavior could be compared with predictions from energy optimality: that is, minimizing models of total energy consumption or effort. For instance, we could hypothesize minimize an effort-like function of the form: $c_1 (F_L)^{\gamma} + c_2 (F_R)^{\gamma}$ subject to the task constraint of $\lambda F_L + (1-\lambda) F_R = \alpha F_{max}$, and compare predictions with data for fixed constants, or infer the constants (c_1, c_2, γ) so as to fit the observed data via inverse optimization.

4.4: Conclusions

The data from the human subject trials suggested that our hypothesis that people will produce systematically higher forces for the side that contributes more to the weighted force output was supported. Due to the small sample size, it is difficult to generalize the results, but we plan to run trials on more subjects to see if the trends we found are still present. Our simplified setup was successful in observing trends and the subject's response. The setup provides a good basis for similar experiments that could be performed in the future, allowing the potential for the study of other force sharing concepts and features.

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